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→Found appropriate Lyapunov or "energy" function for continuous BAMs. Proved that every matrix is continuously bidirectionally stable, generalizing the continuous Hopfield model and extending the Cohen-Grossberg Theorem to heteroassociativity. Completed paper "Bidirectional Associatie Memories," submitted to IEEE Trans on Sys, Man, Cyber. Performed fuzzy cognitive map (conceptual computing) knowledge combination experiments on UCSD neural network students. Presented BAM and FCM theory, as invited lectures, to UC Berkeley's Elec Eng Dept and USC's Elec Eng Dept, and to the National Science Foundation.

Performed experiments on all-optical Hughes LCLV (BAM) associative memory. Fabricated matrix masks to represent 10 neurons. Performed computer simulation of moment-term-expansion scale, translation, and rotation invariant feature extraction algorithm for associative memory. Began optical experiments on "counter propagating" (competitive learning) two-wave mixing configuration cast in barium titinate. Explorations of photorefractive media for associative memory.←

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<u>OCCAM 2nd Quarterly R&D Status Report: Sep - Nov 1986</u>

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OCCAM at VERAC

<u>1. Continuous BAM</u>. The bidirectional associative memory (BAM) architecture, developed in the first quarter of OCCAM, was extended to arbitrary continuous-valued neurons. We proved that if the continuous BAM system is given by

$$\dot{a}_i = -a_i + \sum_j S(b_j)\, m_{ij} + I_i ,$$

$$\dot{b}_j = -b_j + \sum_i S(a_i)\, m_{ij} + J_j ,$$

where M is an arbitrary m-by-n connection matrix, S is a bounded monotone increasing (e.g., sigmoid) signal function , and I_i and J_j are constant external inputs to a_i and b_j, then the appropriate Lyapunov or "energy" function E for the network is given by

$$E = -S(A)\, M\, S(B)^T - I\, S(A)^T - J\, S(B)^T + \sum_i \int_0^{a_i} S'(x_i)\, x_i\, dx_i + \sum_j \int_0^{b_j} S'(y_j)\, y_j\, dy_j ,$$

where $A = (a_1, \ldots, a_n)$, $I = (I_i, \ldots, I_n)$, and similarly for B and J.

This proves that <u>every matrix is continuously bidirectionally stable</u>. Among other things, this result trivially generalizes the continuous "Hopfield" model when $M = M^T$. More fundamentally, this result extends the Cohen-Grossberg Theorem for unidirectional autoassociators with fixed-weight symmetric connection matrices C. Now (1) Cohen-Grossberg models can be used for heteroassociation, and (2) when they are, the Cohen-Grossberg Theorem is valid for <u>every</u> connection matrix.

<u>2. Fuzzy Cognitive Map Experiment</u>. We explored conceptual computing by studing the fuzzy cognitive map (FCM) combination technique introduced in the first quarter of OCCAM. Bart was asked to guess lecture in Robert Hecht-Nielsen's neural net course at UCSD. Students received a lecture on FCMs and related technology. As a mandatory homework assignment, the students were given a sample FCM on the complex subject of South African politics. The students were asked to create their own FCM politico-causal interpretation of South African politics. The students consisted of UCSD undergraduates and graduates, UCSD faculty, and San Diego industry participants.

19 student FCMs were combined into one very large FCM using the simplext combination technique--equal weighting (all $w_i = 1$) for each "expert." The student FCMs had on average 8 - 12 nodes and 15 - 25 causal interconnections. The resulting FCM had 36 nodes and 198 connections. These causal maps were manipulated by Bob Sasseen with a FCM software package he developed for the Texas Instruments Explorer and Symbolics Lisp processors.

Due to some ambiguity in the instructions given, some students wrote FCMs with fuzzy weights in [-1, 1] instead of the requested simple bivalent

weights in {-1, 1}. Of course, the students were not experts on South African politics, and many alleged causal connectionsw were rather dubious indeed. Yet, as expected of the simple additive combination technique, most dubious connections had little or not weight in the combined map.

Despite these problems, the combined FCM performed very well. Strictly opposite nodes--such as STRENGTH OF SOUTH AFRICAN ECONOMY and WEAKNESS OF SOUTH AFRICAN ECONOMY, or VIOLENCE and SOCIAL STABILITY--almost invariably had opposite activation values. Running the FCM showed very plausible development of the situation over time.

(Parenthetically, the consensus FCM was rather pessimistic about South Africa's prospects. Nearly all scenarios, starting with various initial conditions, showed the South African situation steadily deteriorating.)

3. BAM Paper. The technical paper "Bidirectional Associative Memories" was completed and submitted for publication to the IEEE Transactions on Systems, Man, and Cybernetics. This paper includes the OCCAM-developed Temporal Associative Memory (TAM) theory.

4. OCCAM Lectures. Bart made three formal (invited) presentations during the second quarter of OCCAM: (1) "Fuzzy Cognitive Maps and Connectionist Architectures" to the EECS Department at UC Berkeley on 30 September, (2) "Adaptive Cogntive Processing" to the National Science Foundation at Woburn, Massachusetts on 8 October, and an extended version of "Adaptive Cognitive Processing" to the Electrical Engineering Department at USC on 31 October. Judging from both immediate audience reaction and the resultant reprint requests (over 120), the talks were well received.

OCCAM at UCSD

During the second quarter of OCCAM at UCSD, concepts developed during the first quarter moved toward implementation. Progress was made in the areas of an all-optical Liquid Crystal Light Valve (LCLV) based neural net system, invariant feature extraction for neural net preprocessing, and dynamic photorefractive associative memory systems. Details of these three efforts are given below.

1. LCLV Neural Net. A neural net system based on the Hughes LCLV was desigined during the first quarter of OCCAM. It employs fully parallel optical feedback, uses the intrinsic sigmoid response of the light valve, and allows dynamic reprogramming of the interconnection matrix at video frame rates. Ultimately, such a system could implement a network of 500 processing elements that converge to steady state in less than 50 msec. Work in the second quarter of OCCAM has moved toward implementation of a system to demonstrate feasibility. The optical system was designed in detail, parts ordered, received, and assembled. Matrix masks were fabricated to implement a 10 neuron system. Final alignment of the system is underway and experiments will commence early in the third quarter.

In the process of designing the system, a novel use was discovered for an existing optical element. At one plane of the system, light coming from a range of different direction must be integrated into a single point that is then anamorphically imaged through the rest of the system. A diffusing screen is used for this purpose. However, the broad distribution of light that occurs on the output side of the diffuser is difficult to capture, even

with low F-number optics, and so the usable light in the system is greatly decreased. It was found that a fiberoptic faceplate served to combine beams arriving from diverse directions and produced at its output face an intensity sum that was much more directed along the normal to the plate than is typically the case for ground glass. While there is some variation light transmission efficiency with input beam angle, wefound it to be quite acceptable for our purposes. This linear phase cancellation operation is new among existing optical devices and should be generally applicable in many systems. (A fiber optic faceplate is an array of very short optical fibers that are fused together with their axes normal to the plate thus formed. The devices were available to us as cosmetic rejects from the Hughes LCLV manufacturing program.)

2. Invariant Feature Extraction Algorithm. A scale, rotation, and translation invariant feature extractionalgorithm was developed during the first quarter of OCCAM. A computer simulation produced 25 feature moments of chosen sample patterns, in this case letters of the alphabet. Continued simulation during the second quarter has allowed a subset of twelve moments fromthe initial 25 to be chosen that provide the best discrimination capability. An optical correlation system using computer-generated holographic filters has been designed that will allow simultaneous extraction of all 12 moments. These moments will then serve as the inputs to a neural net that will be trained to classify scaled, rotated, and translated innputs. Fabrication of the required holographic filters is currently underway. Classification networks to be tried include the continous Cohen-Grossberg (BAM), back propagation, and Kohonen's "self-organizing" system (i.e., Grossberg's 1976 competitive learning model).

3. Photorefractive Associative Memory. Multiwave mixing, and optical storage in photorefractive crystals, have been identified by a number of research groups as potentially useful in neural net applications. Fundamental operations that will need to be done include image amplification, thresholding, and incoherent-to-coherent conversion. At UCSD, during the second quarter of OCCAM, we began experments to characterize these effects in a "counter propagating" two-wave mixing configuration done in barium titinate. ("Counter propagation" is the name Hecht-Nielsen gave his implementation of the 1976 Grossberg competitive learning model, in order, apparently, to contrast it with back propagation.) The "counter propagating" configuration allows beams to enter the crystal from opposite facesof the crystal, thereby recording a reflection type hologram. The reflection configuration is desirable since it allows greater use of the volume of the crystal, and it removes undiffractedlight from the system during hologram readout. Image amplification with gains of up to 30 times have been achieved, and much higher results can be expected.

A preliminary system design using photorefractive elements has been completed. It will implementf an attentional-orienting system of the type introduced by Grossberg. Such systems have the capability to adaptively code arbitrary input patterns, i.e., no pre-orthogonalization is necessary. Recall can use time sequential pattern matching for best-fit classification.